

# Unparticles in Gluodynamics

A.T. Alan\*

Department of Physics, Abant Izzet Baysal University, 14280 Bolu, Turkey

The virtual effects of unparticle physics on the two-gluon jets production are explored for CERN LHC. It is found that depending on the scale dimension, unparticles can give rise to substantial enhancements in the transverse momentum and pseudo-rapidity distributions of hadronic cross sections, up to a factor of four-orders of magnitude.

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*Introduction.* Recently, Georgi [1] has introduced the concept of unparticle physics as a scale invariant field theory, which proved to be very interesting and attractive as displayed by the number of publications on the subject [2]. Fields of unparticle physics do not manifest themselves as particles unlike the fields of conventional field theories. The scheme is as follows. The fields of a scale invariant sector with a nontrivial infrared fixed point -Banks and Zaks ( $\mathcal{BZ}$ ) fields- [3] and the fields of Standard Model (SM) can coexist and interact via the exchange of particles of large mass scale  $M_U$  at very high energies. Below  $M_U$ , non-renormalizable operators are induced giving the interactions

$$\frac{1}{M_U^k} \mathcal{O}_{SM} \mathcal{O}_{BZ}$$

in the generic form. Where  $\mathcal{O}_{SM}$  and  $\mathcal{O}_{BZ}$  are operators built out of  $SM$  and  $\mathcal{BZ}$  fields with scale dimensions  $d_{SM}$  and  $d_{BZ}$ , respectively. Renormalizable couplings of  $\mathcal{BZ}$  fields then cause dimensional transmutation as scale invariance emerges at an energy scale  $\Lambda_U$ . Below  $\Lambda_U$ ,  $\mathcal{BZ}$  operators match onto unparticle operators giving the non-renormalizable interactions

$$C_U \frac{\Lambda_U^{d_{BZ}-d_U}}{M_U^k} \mathcal{O}_{SM} \mathcal{O}_U$$

where the non-integral number  $d_U$  is the scaling dimension of the unparticle operator  $\mathcal{O}_U$  constructed out of the new fields (unparticles) and  $C_U$  is a coefficient function. Following this suggestion many studies have been performed to explore the effects of unparticles on low energy dynamics [4]. Our aim in this letter is to explore the effects of virtual unparticles on the two-gluon jets production which will be one of the most observed processes at the forthcoming LHC experiments.

At hadron colliders jet production predominates all the other processes. Its understanding in detail is crucial both for precision tests of perturbative Quantum Chromodynamics (pQCD) and the search for new physics. Data from the experiments at the Tevatron are in good agreement with the next-to-leading order (NLO) pQCD predictions [5, 6]. Specifically the LHC, with 14 TeV center of mass energy and a high luminosity of  $10^5 \text{ pb}^{-1}$ , will provide very large accessible kinematic range, which

in turn will present unprecedented discovery potential. Cross section measurements at the LHC will cover jets with transverse momenta of order 4 TeV to probe the shortest distances ever reached.

*Two-gluon jets at hadronic collisions.* In this letter, we exploit the implications of unparticle physics on two-gluon jets production in  $pp$  collisions via the partonic  $gg \rightarrow gg$  scattering at LO, in the framework of gluodynamics which describes gluons and their selfinteractions only. Gluon jets show differences compared to quark jets in their widths, hadron multiplicities and ratios of multiplicities stemming from different color charges of quarks and gluons. Great progress has been made on these differences by both theorists and experimentalists [7]. As we do not expect a leading contribution for this production, the analysis of the  $q\bar{q}$  initial state will not be included in present work. Gluon fusion as an initial state is largely dominant compared to those of quark-antiquark annihilation and quark-gluon scattering in most of the production channels at the LHC energies, indeed.

The relevant tree level Feynman graphs are shown in Fig. 1 in which the upper three graphs correspond to the contribution of virtual scalar and tensor unparticles, as vector unparticles do not couple to the gluons. The lower four ones are the usual tree level SM diagrams. To derive

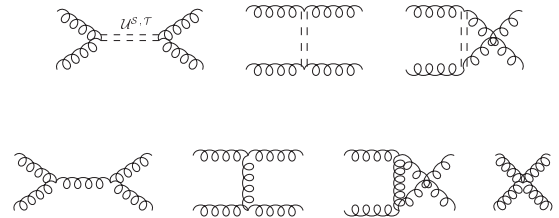


FIG. 1: The leading order Feynman diagram for  $gg \rightarrow gg$  scattering with the contribution of unparticles.

the corresponding differential cross sections we work in the axial gauge by taking the gluon propagator as follows:

$$\Delta_{\mu\nu} = \frac{-i}{q^2} (g_{\mu\nu} - \frac{q^\mu q^\nu}{q^2}). \quad (1)$$

In summing over the physical, transverse gluon polariza-

tions in the calculations of amplitudes squared, we use

$$\sum_{\lambda} \epsilon_{\mu}(\lambda, p) \epsilon_{\nu}^*(\lambda, p) = (-g_{\mu\nu} - \frac{n^{\mu} p^{\nu} + n^{\nu} p^{\mu}}{n \cdot p})$$

where the fourvector  $n$  is defined as  $n = (p_0, -\vec{p})$ . Propagators for the scalar and the tensor unparticles [1, 8], derived from a scale invariance principle, are

$$\begin{aligned} \Delta^S(q_{\mathcal{U}}^2) &= \frac{i A_{d_{\mathcal{U}}}}{2 \sin(\pi d_{\mathcal{U}})} (-q_{\mathcal{U}}^2)^{d_{\mathcal{U}}-2} \\ \Delta_{\mu\nu, \rho\sigma}^T(q_{\mathcal{U}}^2) &= \frac{i A_{d_{\mathcal{U}}}}{2 \sin(\pi d_{\mathcal{U}})} (-q_{\mathcal{U}}^2)^{d_{\mathcal{U}}-2} T_{\mu\nu, \rho\sigma}(q) \end{aligned} \quad (2)$$

respectively, where

$$A_{d_{\mathcal{U}}} = \frac{16\pi^2 \sqrt{\pi}}{(2\pi)^{2d_{\mathcal{U}}}} \frac{\Gamma(d_{\mathcal{U}} + \frac{1}{2})}{\Gamma(d_{\mathcal{U}} - 1) \Gamma(2d_{\mathcal{U}})} \quad (3)$$

is the normalization factor of  $d_{\mathcal{U}}$ -body phase space of massless particles and the tensor  $T^{\mu\nu, \rho\sigma}$  in Eq. (2) is given by

$$\begin{aligned} T_{\mu\nu, \rho\sigma}(q) &= \frac{1}{2} \{ \pi_{\mu\rho}(q) \pi_{\nu\sigma}(q) + \pi_{\mu\sigma}(q) \pi_{\nu\rho}(q) \\ &\quad - \frac{2}{3} \pi_{\mu\nu}(q) \pi_{\rho\sigma}(q) \} \end{aligned} \quad (4)$$

with

$$\pi_{\mu\nu}(q) = -g_{\mu\nu} + \frac{q_{\mu} q_{\nu}}{q^2} \quad (5)$$

for transverse and traceless tensor unparticle operator. In conformal field theories (CFT) this tensor is given by [9]

$$\begin{aligned} T_{\mu\nu, \rho\sigma} &= \frac{1}{2} \left[ (g_{\mu\rho} g_{\nu\sigma} + \mu \leftrightarrow \nu) + \frac{[4 - d(d+1)]}{2d(d-1)} g_{\mu\nu} g_{\rho\sigma} \right. \\ &\quad - 2 \frac{(d-2)}{d} \left( g_{\mu\rho} \frac{k_{\nu} k_{\sigma}}{k^2} + g_{\mu\sigma} \frac{k_{\nu} k_{\rho}}{k^2} + \mu \leftrightarrow \nu \right) \\ &\quad + 4 \frac{(d-2)}{d(d-1)} \left( g_{\mu\nu} \frac{k_{\rho} k_{\sigma}}{k^2} + g_{\rho\sigma} \frac{k_{\mu} k_{\nu}}{k^2} \right) \\ &\quad \left. + 8 \frac{(d-2)(d-3)}{d(d-1)} \frac{k_{\mu} k_{\nu} k_{\rho} k_{\sigma}}{(k^2)^2} \right] \end{aligned} \quad (6)$$

The structures of vertices [10, 11] for the effective interactions of scalar and tensor unparticles with gluons are SM gauge invariant and are given, respectively, by

$$\lambda_0 \frac{1}{\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}}} G_{\alpha\beta} G^{\alpha\beta} O_{\mathcal{U}} \quad \text{and} \quad \lambda_2 \frac{1}{\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}}} G_{\mu\alpha} G_{\nu}^{\alpha} O_{\mathcal{U}}^{\mu\nu} \quad (7)$$

where  $G^{\alpha\beta}$  denotes the gluon field strength and  $\lambda_0, \lambda_2$  are dimensionless coupling constants for the scalar and the tensor unparticles, respectively.

After helicity and color averaging the partonic differential cross section in the case of the scalar unparticle exchange is obtained as

$$\begin{aligned} \frac{d\hat{\sigma}^S}{d\hat{t}} &= \frac{1}{256\pi\hat{s}^2} \left\{ A_S^2 \left[ \frac{\hat{s}^4}{(\hat{s})^{4-2d_{\mathcal{U}}}} + \frac{\hat{t}^4(\hat{t}^2 + \hat{u}^2)^2}{\hat{s}^4(-\hat{t})^{4-2d_{\mathcal{U}}}} + \frac{\hat{u}^4(\hat{t}^2 + \hat{u}^2)^2}{\hat{s}^4(-\hat{u})^{4-2d_{\mathcal{U}}}} \right] + A_S^2 \left\{ \cos(\pi d_{\mathcal{U}}) \left[ \frac{\hat{t}^2(\hat{t}^2 + \hat{u}^2)}{8(\hat{s})^{2-d_{\mathcal{U}}}(-\hat{t})^{2-d_{\mathcal{U}}}} \right. \right. \right. \\ &\quad \left. \left. + \frac{\hat{u}^2(\hat{t}^2 + \hat{u}^2)}{8(\hat{s})^{2-d_{\mathcal{U}}}(-\hat{u})^{2-d_{\mathcal{U}}}} \right] + \frac{\hat{t}^2\hat{u}^2(\hat{t}^4 + 6\hat{u}^2\hat{t}^2 + \hat{u}^4)}{8\hat{s}^4(-\hat{t})^{2-d_{\mathcal{U}}}(-\hat{u})^{2-d_{\mathcal{U}}}} \right\} + 12\pi A_S \alpha_s \left\{ \frac{\cos(\pi d_{\mathcal{U}})}{(\hat{s})^{2-d_{\mathcal{U}}}} \left[ \frac{1}{2\hat{t}} (\hat{s}^3 - 7\hat{s}^2\hat{u} - 8\hat{s}\hat{u}^2 - 2\hat{u}^3) \right. \right. \\ &\quad \left. \left. + \frac{1}{2\hat{u}} (\hat{s}^3 - 7\hat{s}^2\hat{t} - 8\hat{s}\hat{t}^2 - 2\hat{t}^3) + \hat{s}^2 + 2\hat{t}\hat{u} \right] + \frac{1}{(-\hat{t})^{2-d_{\mathcal{U}}}} \left[ \frac{\hat{t}^2(\hat{t}^3 - \hat{u}\hat{t}^2 + \hat{u}^2\hat{t} - \hat{u}^3)}{2\hat{s}^3} \right. \right. \\ &\quad \left. \left. - \frac{\hat{t}^2(2\hat{s}^5 + 9\hat{u}\hat{s}^4 + 20\hat{u}^2\hat{s}^3 + 20\hat{u}^3\hat{s}^2 + 16\hat{u}^4\hat{s} + 8\hat{u}^5)}{2\hat{u}\hat{s}^4} + \frac{\hat{t}^2(\hat{s} + 2\hat{t})^2(\hat{s}^2 + \hat{t}\hat{s} + \hat{t}^2)}{\hat{s}^4} \right] \right. \\ &\quad \left. + \frac{1}{(-\hat{u})^{2-d_{\mathcal{U}}}} \left[ \frac{\hat{u}^2(\hat{u}^3 + \hat{u}\hat{t}^2 - \hat{u}^2\hat{t} - \hat{t}^3)}{2\hat{s}^3} - \frac{\hat{u}^2(2\hat{s}^5 + 9\hat{t}\hat{s}^4 + 20\hat{t}^2\hat{s}^3 + 20\hat{t}^3\hat{s}^2 + 16\hat{t}^4\hat{s} + 8\hat{t}^5)}{2\hat{t}\hat{s}^4} \right. \right. \\ &\quad \left. \left. + \frac{\hat{u}^2(\hat{s} + 2\hat{u})^2(\hat{s}^2 + \hat{u}\hat{s} + \hat{u}^2)}{\hat{s}^4} \right] \right\} \right\} + \frac{d\hat{\sigma}_0}{d\hat{t}} \end{aligned} \quad (8)$$

where

$$A_S = \frac{8\lambda_0^2 A_{d_{\mathcal{U}}}}{\sin(\pi d_{\mathcal{U}}) \Lambda^{2d_{\mathcal{U}}}} \quad (9)$$

and

$$\frac{d\hat{\sigma}_0}{d\hat{t}} = \frac{9\pi\alpha_s^2}{2\hat{s}^2} \frac{(\hat{s}^2 + \hat{t}\hat{s} + \hat{t}^2)^3}{\hat{s}^2\hat{t}^2\hat{u}^2} \quad (10)$$

is the differential cross section for the SM prediction at LO.  $d\hat{\sigma}/d\hat{t}$  in Eq. (8) consists of terms that come from

unparticle contributions ( $A_S^2$  terms), interference of gluons and unparticles ( $A_S$  terms), as well as the SM term  $d\hat{\sigma}_0/d\hat{t}$ . The corresponding differential cross section for

the tensor unparticle exchange with traceless tensor operator in Eq. (4) is given by

$$\begin{aligned} \frac{d\hat{\sigma}^T}{d\hat{t}} = & \frac{1}{32\pi\hat{s}^2} \left\{ A_T^2 \left[ \frac{\hat{t}^4 + \hat{u}^4}{(\hat{s})^{4-2d_U}} + \frac{\hat{s}^4 + \hat{u}^4}{(-\hat{t})^{4-2d_U}} + \frac{\hat{s}^4 + \hat{t}^4}{(-\hat{u})^{4-2d_U}} \right] + \frac{A_T^2}{4} \left\{ \cos(\pi d_U) \left[ \frac{\hat{u}^4}{(\hat{s})^{2-d_U}(-\hat{t})^{2-d_U}} + \frac{\hat{t}^4}{(\hat{s})^{2-d_U}(-\hat{u})^{2-d_U}} \right] \right. \right. \\ & + \left. \frac{\hat{s}^4}{(-\hat{t})^{2-d_U}(-\hat{u})^{2-d_U}} \right\} + 3\pi A_T \alpha_s \left\{ \frac{-\cos(\pi d_U)}{(\hat{s})^{2-d_U}} \left[ \frac{\hat{t}^5 + 2\hat{u}\hat{t}^4 + \hat{u}^4\hat{t} + 2\hat{u}^5}{\hat{t}\hat{s}^2} + \frac{\hat{u}^5 + 2\hat{t}\hat{u}^4 + \hat{t}^4\hat{u} + 2\hat{t}^5}{\hat{u}\hat{s}^2} - \frac{2(\hat{t}^4 + \hat{u}^4)}{\hat{s}^2} \right] \right. \\ & + \frac{1}{(-\hat{t})^{2-d_U}} \left[ \hat{s}(\hat{t} - \hat{u}) + \frac{2\hat{t}^5 + 13\hat{u}\hat{t}^4 + 28\hat{u}^2\hat{t}^3 + 25\hat{u}^3\hat{t}^2 + 10\hat{u}^4\hat{t} + \hat{u}^5}{\hat{u}\hat{s}^2} + \frac{\hat{u}^4 + \hat{s}^2(2\hat{u}^2 - \hat{s}^2 - \hat{t}^2)}{\hat{s}^2} \right] \\ & + \left. \frac{1}{(-\hat{u})^{2-d_U}} \left[ \hat{s}(\hat{u} - \hat{t}) + \frac{2\hat{u}^5 + 13\hat{t}\hat{u}^4 + 28\hat{t}^2\hat{u}^3 + 25\hat{t}^3\hat{u}^2 + 10\hat{t}^4\hat{u} + \hat{t}^5}{\hat{t}\hat{s}^2} + \frac{\hat{t}^4 + \hat{s}^2(2\hat{t}^2 - \hat{s}^2 - \hat{u}^2)}{\hat{s}^2} \right] \right\} \Bigg\} + \frac{d\hat{\sigma}_0}{d\hat{t}} \quad (11) \end{aligned}$$

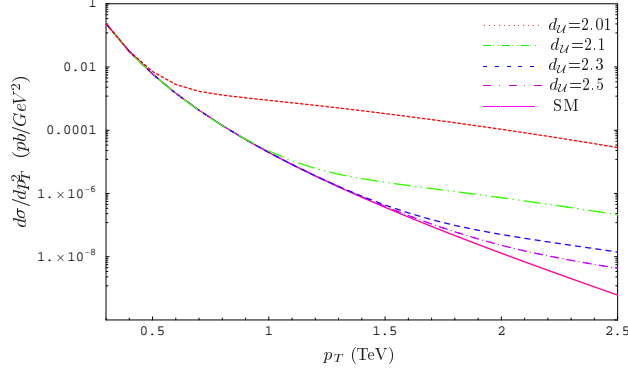


FIG. 2: Differential cross section  $\frac{d\sigma}{dp_T^2}$  as a function of  $p_T$  for two jet signals at the LHC with scalar unparticle exchange plus SM contribution. We have set  $\lambda_0=1$  and  $\Lambda=1$  TeV.

where

$$A_T = \frac{\lambda_2^2}{16\lambda_0^2} A_S.$$

We have checked the calculation of the differential cross section for the tensor unparticle propagator in CFT with  $T_{\mu\nu,\rho\sigma}$  given in Eq. (6) and obtained exactly the same result. But in CFT due to the constrain  $d_U \geq 4$  on the scale dimension for the tensor unparticle operator, the unparticle exchange contribution to the hadronic distributions are negligible small. Hence, in the numerical analysis we have taken the range of  $2 < d_U < 3$  (conformal invariance is not imposed further on).

Total hadronic cross section is calculated as a composition of partonic cross section multiplied by parton densities  $f_i(x_i, Q^2)$  which are evaluated at a factorization scale  $Q$ . The longitudinal momentum fractions of incoming gluons  $x_i = \frac{p_i}{P}$ , are related to the observed jet

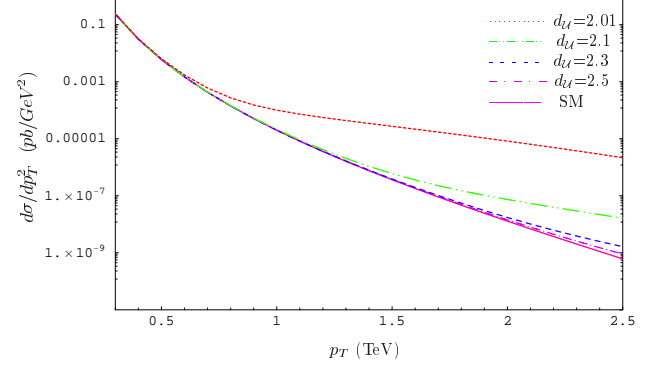


FIG. 3: Differential cross section  $\frac{d\sigma}{dp_T^2}$  as a function of  $p_T$  for two jet signals at the LHC with tensor unparticle exchange plus SM contribution. we have set  $\lambda_2=1$  and  $\Lambda=1$  TeV.

variables, transverse momenta,  $p_{iT}$  and rapidities,  $y_i$  by

$$x_1 = \frac{p_T}{\sqrt{s}}(e^{y_1} + e^{y_2}), x_2 = \frac{p_T}{\sqrt{s}}(e^{-y_1} + e^{-y_2}) \quad (12)$$

with the transverse momentum conservation  $p_{1T} = p_{2T} = p_T$ . Then, the final hadronic state describing the production of two-gluon jets at LO is specified by the factorization formula

$$\begin{aligned} \frac{d^3\sigma}{dy_1 dy_2 dp_T^2} = & \sum_{i,j} \left( \frac{1}{1 + \delta_{ij}} \right) \frac{\hat{s}}{s} [f_i(x_1, Q^2) f_j(x_2, Q^2) \\ & + f_i(x_2, Q^2) f_j(x_1, Q^2)] \frac{d\hat{\sigma}}{d\hat{t}} \quad (13) \end{aligned}$$

*Numerical results and conclusions.* In Figs. 2 and 3 we plot  $p_T$  distributions of hadronic cross sections for two-gluon jets production at the LHC by taking into account

the contributions of the scalar and the tensor unparticles, respectively, for various  $d_U$  values by setting the parameters  $\lambda_0 = \lambda_2 = 1$  and  $\Lambda = 1$  TeV. We have used CTEQ5 [12] gluon distributions and have evaluated them at the scale  $Q = p_T$  in all of our numerical computations. Effects of virtual unparticles become quite large for the  $p_T$  values greater than 1 TeV. For instance, for  $d_U = 2.01$  hadronic differential cross sections at  $p_T = 2$  TeV are  $10^{-4}$  pb/GeV<sup>2</sup> for scalar unparticle plus SM and  $10^{-5}$  pb/GeV<sup>2</sup> for the tensor unparticle plus SM contributions, respectively (the SM value is  $1.2 \times 10^{-8}$  pb/GeV<sup>2</sup>). The tensor contribution is about one order less compared to that of scalar contribution on the average. These contributions decrease with increasing  $d_U$  values. The corresponding values are  $5 \cdot 10^{-8}$  pb/GeV<sup>2</sup> and  $1.7 \times 10^{-8}$  pb/GeV<sup>2</sup>, respectively, for  $d_U = 2.3$ . Figs. 4 and 5 show the pseudo-

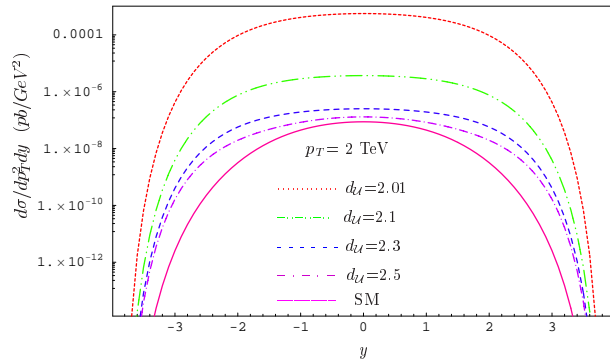


FIG. 4: The differential cross section for two gluon jets production at the LHC as a function of pseudo-rapidity interval  $y$ , at  $y_{boost}=0$  and  $p_T=2$  TeV, for the scalar unparticle exchange plus SM contribution. We have set  $\lambda_0=1$  and  $\Lambda=1$  TeV

rapidity distributions of cross sections for two-gluon jets production at the LHC with scalar and tensor unparticle contributions, respectively. The cross sections are plotted as function of pseudo-rapidity interval  $y = y_1 - y_2$  at  $y_{boost} = (y_1 + y_2)/2 = 0$ . Here,  $y$  is the pseudo-rapidity of a parton in the center of mass frame while  $y_{boost}$  is the pseudo-rapidity of parton center of mass frame with respect to the hadron center of mass frame. For  $d_U = 2.01$  and the interval  $y = 1$  the hadronic differential cross sections at  $p_T = 2$  are about  $4.0 \times 10^{-4}$  and  $3.2 \times 10^{-5}$  pb/GeV<sup>2</sup> for the scalar and the tensor unparticle cases, respectively. The LO SM differential cross section at the same  $y$  and  $p_T$  values is  $4.5 \times 10^{-8}$  pb/GeV<sup>2</sup>. It is possible to apply an SM  $K$  factor to obtain reliable NLO predictions but we have not included it in our calculations since  $K$  values change depending on the different pseudo-rapidity intervals [6].

To summarize, we have studied the production of  $gg$  jet pairs associated with unparticle physics at the LHC energies. In the analysis we have not included  $q\bar{q}$  initial

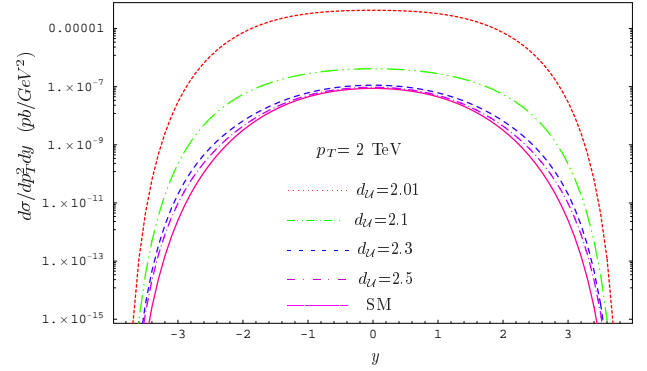


FIG. 5: The differential cross section for two gluon jets production at the LHC as a function of pseudo-rapidity interval  $y$ , at  $y_{boost}=0$  and  $p_T=2$  TeV, for the tensor unparticle exchange plus SM contribution. We have set  $\lambda_2=1$  and  $\Lambda=1$  TeV

state. The LO SM contribution originated from  $q\bar{q}$  annihilation at  $p_T=3$  TeV is about 15 % and it decreases down to about 2 % at  $p_T=1$  TeV and % 0.8 at  $p_T=0.5$  TeV. For an interval of scale dimension  $2 < d_U < 3$  we obtained large enhancements (approximately 10000 times) in  $p_T$  and pseudo-rapidity distributions of cross sections; specifically for  $d_U$  values close to 2. It is expected that even higher enhancement is possible if one extrapolates the interval to  $1 < d_U < 2$ . We hope that our predictions provide a reliable explanation for the deviations from SM values of cross section distributions for  $gg$  jet pairs to be produced at the LHC, in the case of possible existence of unparticle physics.

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\* alan\_a@ibu.edu.tr

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